COSMIC RAY INTENSITY VARIATIONS AND TWO TYPES OF HIGH SPEED SOLAR STREAMS

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Abstract. This study deals with the short-term variations of cosmic ray intensity during the interval 1973–78. Daily means of high latitude neutron and meson monitors from the same station and those of a low latitude neutron monitor have been analysed using the Chree method of superposed epochs. The zero epoch for the Chree analyses corresponds to the day of a substantial increase ($\Delta V \gtrsim 200$ km s^{-1}) in the solar wind speed to values of $\gtrsim 550$ km s^{-1} and which persists at such high values for an interval of at least three days. The investigation reveals the existence of two types of cosmic ray intensity variations with distinctly different spectral characteristics. During the interval 1973–76, relative changes in the neutron and meson monitor rates are nearly equal indicating an almost flat rigidity spectrum of variation. During 1977–78, however, the spectrum acquires a negative spectral character similar to that observed for Forbush decreases. We suggest that events of the interval 1973–76 are essentially due to high speed streams associated with solar coronal holes and that events of the interval 1977–78 are due to fast streams from solar active regions with flare activity.

1. Introduction

A number of studies have dealt with the long-term (solar cycle) variation of galactic cosmic ray intensity and its association with various solar, interplanetary and geophysical parameters; often these have revealed contradictory results (Forbush, 1958, and references therein; Rao, 1972; Pomerantz and Duggal, 1974; Moraal, 1976; Morfill *et al.*, 1976; Hatton, 1980; Nagashima and Morishita, 1980a, b). The lag between the cosmic ray intensity variations and solar activity parameters such as the sunspot number and the coronal green line and its interpretation in terms of the heliospheric boundary have also run into difficulty (Rao, 1972; Van Allen, 1980; Venkatesan *et al.*, 1980). It is also relevent to mention about the attempted correlation with solar wind speed and interplanetary magnetic field magnitude and/or fluctuation; again these studies have also failed to account for the long-term variation in cosmic ray intensity (Mathews *et al.*, 1971; Hedgecock, 1975; Yoshimura, 1977; Barichello, 1978; and Feldman *et al.*, 1979). Thus of late there has been a general recognition that it may not be always meaningful to take an average value of solar wind speed for long-term correlative studies.

From a limited study over 5 solar rotations, Streenvasan and Johnson (1968) have observed a negative correlation of 0.4 between daily values of cosmic ray intensity and solar wind speed; this correlation improves to -0.8 for a single Forbush decrease available for study during that period. Barichello (1978) has pointed out a significant

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negative correlation between the two parameters over short periods of a few solar rotations. Recent studies of Iucci *et al.* (1979) and Shukla *et al.* (1979) reveal that the correlation improves for periods of high speed solar wind streams, if large cosmic ray intensity changes during Forbush decreases are excluded (see also Duggal, 1977, and references therein). This has led the above authors to distinguish two types of effects on cosmic ray intensity due to high speed solar wind streams with origins from two different solar sources such as coronal holes and solar flares (Dryer, 1974; Burlaga, 1979). The coronal hole origin of 'monster streams' during the declining phase of sunspot cycle 20 when solar activity was usually low, has been well-documented and reviewed (e.g., Zirker, 1977; Hundhausen, 1979). Furthermore, Agrawal *et al.* (1980) have demonstrated the significant effect of the relative sizes of the solar-polar coronal holes in the two hemispheres, on cosmic ray north–south asymmetry for well-selected individual events. Their average behavior and long-term association has also been recently reported (Agrawal *et al.*, 1978; Hundhausen *et al.*, 1980; Venkatesan *et al.*, 1980).

The essential purpose of this report is to further investigate the differences in the effects of the above-mentioned two types of high speed solar wind streams on cosmic ray intensity for the period 1973–78. We have used the published interplanetary medium data plots (King, 1977, 1979) for the selection of events, and the daily mean intensity of cosmic rays observed by the high latitude neutron and meson monitors of Inuvik and the low latitude (high cut-off rigidity) neutron monitor at Tokyo.

2. Selection of Events and Data Analyses

Using the plots of hourly values of interplanetary parameters (King, 1977, 1979), we have selected the zero epoch days which satisfy the following criteria:

(1) The solar wind speed (V) should increase substantially over a short period ($\Delta V \gtrsim 200$ km s^{-1} in $\lesssim 24$ hr), reaching a maximum value of $\gtrsim 550$ km s^{-1}.

(2) The solar wind speed should persist at high values for at least 3 days after the increase. Note that the total number of events of such high speed solar wind streams decreases significantly during the years 1977 and 1978, a period of increasing solar activity as revealed by sunspot number.

(3) No large Forbush decreases (FD) of magnitude $\gtrsim 4\%$ in cosmic ray intensity, as seen by Inuvik neutron monitor, should occur within ± 3 days of zero day. The purpose of this restriction is to avoid their influence on the average behaviour being studied, and its importance cannot but be stressed, particularly for intervals when large Forbush decreases such as those of February 15 and April 30, 1978 occur.

(4) Events with more than two days of missing data of cosmic ray intensity in any one station are also not included for Chree analysis.

We have adopted the Chree method of superposed epochs and carried out the analysis for the selected events, to determine their average behaviour. The results are shown in Figure 1 for three intervals of 2 years each (1973–74, 1975–76, 1977–78) for neutrons (Inuvik and Tokyo) and mesons (Inuvik). The plots refer to the percent deviation of the

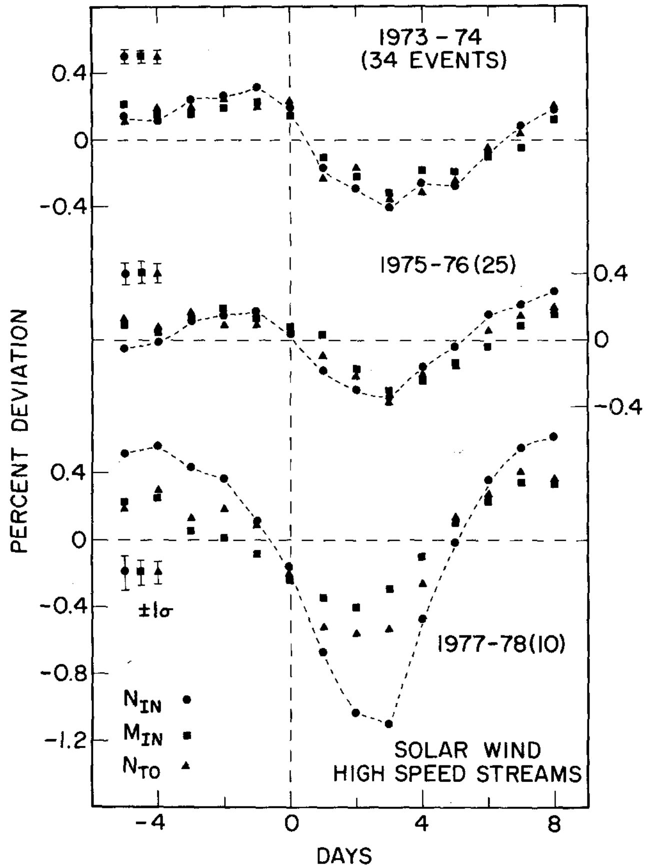

Fig. 1. Results of the superposed epoch Chree analysis from −5 to +8 days with respect to zero epoch days. The percent deviation of the daily mean cosmic ray intensity observed by the Inuvik neutron (N_{IN}) and meson (M_{IN}) detectors and those of Tokyo neutrons (N_{TO}) for a number of events (noted in parentheses) are shown for the period 1973–78. Deviations for each event are obtained from the overall average of the 14 days indicated earlier. Zero day corresponds to the starting day of the high speed solar wind streams (see text for detailed selection criteria). Note their larger occurrence rate during low sunspot activity period of 1973–76.

daily mean count rates of the appropriate cosmic ray data. It is to be pointed out that for each event the cosmic ray intensity is first averaged for 14 days (from −5 day to +8 days with respect to zero epoch day) and this average is used to calculate the percent deviation for each day. The standard error of the mean is derived for each day of the epoch from the actual scatter of the individual percent deviation, and are representative of their upper limit estimates. Some representative standard errors ($\pm 1\sigma$) are also shown in Figure 1. For Tokyo, these are usually comparable to those of Inuvik mesons. The number of events studied during each epoch is given in brackets beside the year(s). Note that the average behaviour of cosmic ray intensity in the three sets of plots in Figure 1 is similar for all the three periods.

During the four-year interval 1973–76, note the onset of a substantial decrease in cosmic ray intensity, starting ~zero day, with almost similar time behaviour as well as an equal magnitude of the total decrease ($\approx 0.6\%$) for the three different monitoring systems. In contrast, it is to be emphasized that during 1977–78 a differential effect in the intensity decrease in the three detectors is clearly observed. We attribute this to the difference in the rigidity response of the detectors. A larger decrease ($\approx 1.7\%$) is registered in the Inuvik neutron intensity by the detector with a low median rigidity response ($\approx$ 8 GV), whereas roughly a factor of two smaller decrease in intensity is seen by the other two detectors (Inuvik mesons and Tokyo neutrons; median rigidity $\approx$ 30 GV). In the latter case we mention, in passing, the onset of a gradual decrease in intensity, from 2–3 days prior to the zero epoch day. This could possibly be the effect of other sources simultaneously present during a high sunspot activity period. However, the point we wish to make is that the maximum decrease of intensity is observed 2–3 days after the zero epoch day, which is similar to that for the interval 1973–76.

Thus, the rigidity spectrum of the variation (as implied by the plots) for both the intervals 1973–74 as well as 1975–76 is independent of particle rigidity. On the other hand, the events of 1977–78 are composed of rigidity-dependent variations, whose magnitude decreases with rigidity. We compare the magnitude of the total decreases seen in the neutron intensities at Tokyo and Inuvik, and the meson and neutron intensities of Inuvik. We calculate the spectral exponent of the variation (β) during 1973–76; β is found to be $\gtrsim 0$, a value usually obtained for the diurnal variation of cosmic ray intensity (e.g., Rao, 1972). Similar calculations for 1977–78, however, yield a value for $\beta \approx -1.0$ (upper cut-off rigidity of the particles is assumed to be ~200 GV), which in general is representative of the Forbush-type decreases as well as the long-term modulation of cosmic ray intensity (e.g., Lockwood, 1971; Morfill *et al.*, 1976; Verschell *et al.*, 1975). Thus, the difference in the effects on cosmic ray intensity produced by the high speed solar wind stream during the two different periods is quite obvious.

We wish to establish the similarity of the relative effects observed in 1977–78 with actual Forbush decreases and carry out a complementary study. In this analysis, the zero epoch day is made to coincide with the onset of well-defined clearly identifiable Forbush decreases (say amplitude $\gtrsim 4\%$). Note that the Forbush decreases of February 15 and April 30, 1978 are very pronounced in magnitude and anisotropy, and hence these two events have been excluded from the study to prevent them from dominating the average. The results of the Chree analyses are shown in Figure 2. The magnitude of the total decrease for Inuvik mesons and Tokyo neutrons are approximately the same, and are a factor of ≈ 0.4 of the Inuvik neutrons. The number of Forbush decreases during 1973–76 was 9, during 1977 it was 1 and during 1978 it was 10. The decreases were large and predominant only during 1978, a period of high solar activity. In view of the atmospheric (temperature) effect for mesons, and for better statistics all the Forbush decreases during the interval 1973–76 were combined together. Note that the results for small as well as large Forbush decreases are essentially the same. Similar conclusions can be drawn from a study of seven well-defined individual Forbush decreases of 1977–79 with amplitudes $\gtrsim 6\%$. The total magnitude of the decrease is

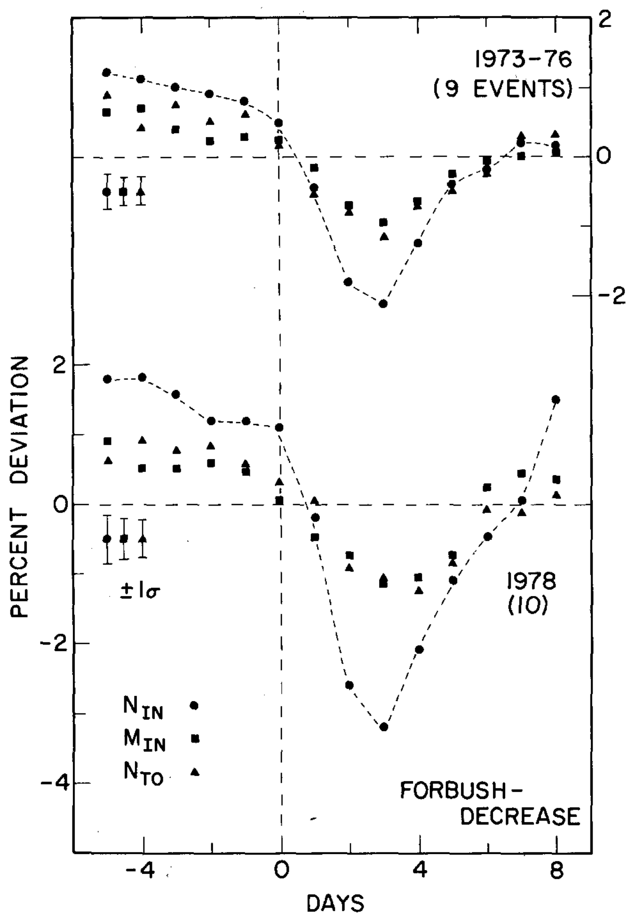

Fig. 2. Same as Figure 1, with zero day representing the start of the Forbush decrease in cosmic ray intensity. Hourly values are used to time-shift the data appropriately, so that the initial hour of intensity decrease seen by Inuvik neutron monitor is always taken as the 24th hour of the zero day in all three cases. The large Forbush decrease events of February 15 and April 30, 1978 are not included (see text for details).

derived from the hourly intensity plots. Again, the ratios in the two cases are roughly the same with an average value $\approx 0.54 \pm 0.04$ indicative of the negative spectra of the variation.

3. Discussion and Conclusions

Iucci *et al.* (1979) and Shukla *et al.* (1979) have shown the close correspondence between the cosmic ray intensity decreases observed by high latitude neutron monitors and the increase in solar wind speed during the period of high speed streams which probably originate in coronal holes. They have also shown that the high speed streams produced by solar flares are accompanied by Forbush decreases whose amplitudes are not directly correlated with the increase in solar wind speed. These latter decreases are usually large and are dependent on the location of the solar flares. During 1973–76, we observe a large number of high speed solar wind streams most of which appear to be associated with coronal holes (e.g., Hundhausen, 1979). We have carried out the following consistency check. Assuming a constant speed of travel for the solar wind from the Sun to the Earth, we find that more than half of these 59 high speed streams in the interval 1973–76 are not at all in time-coincidence (within ± 12 hr) with any solar flare of importance $\geq 1n$ on the visible solar disk. In contrast we note, however, that the total number of high speed streams satisfying our selection criteria are only 10 in 1977–78, a period during which solar activity is approaching its maximum as indicated by sunspot number. Again assuming constant speed, we now find that all of these 10 streams are in time-association with solar flares. Nevertheless, it is possible that during this interval one perhaps sees a corotating fast stream which originated in a solar flare much earlier, and not in a fast stream out of a coronal hole.

Thus from the present study, we have observed a difference in the rigidity spectrum of the short-term variation of cosmic ray intensity; this is attributed to the two types of high speed solar wind streams of different solar origin, e.g., coronal hole and solar active regions. This difference in the rigidity spectrum of cosmic ray intensity has implications on the understanding of both the short- and long-term variations of cosmic ray intensity (Hatton, 1980; Venkatesan *et al.*, 1980). We note that the small but significant cosmic ray intensity decreases with almost a flat rigidity spectral variation (exponent ≈ 0) are associated with a large number of high speed streams *essentially predominant during the declining phase* of the sunspot cycle. During such a period, the number as well as the effect of large solar active centres are minimal. This is consistent with the significant residual modulation of galactic cosmic ray intensity during years of minimum sunspot activity (Hatton, 1980), when effects of solar polar coronal holes are more dominant (Simon, 1979; Hundhausen *et al.*, 1980; and Venkatesan *et al.*, 1980). We have also shown that during periods of sunspot maximum activity, these high speed streams decline in number, but the ones present produce much larger decreases in cosmic ray intensity, the magnitude of which decreases with increasing particle rigidity (spectral exponent ≈ -1). In fact during high sunspot activity period, large Forbush decreases are observed during which the solar wind speed hardly exceeds 600 km s^{-1} and that too for much shorter periods. Nevertheless, their effects have been reported at large distances from the Sun (Van Allen, 1980) as well as in the long-term modulation of cosmic ray intensity (Hatton, 1980).

From the results of the time-varying rigidity-dependent effects on cosmic ray intensity demonstrated here during the interval 1973–78 and which are attributed to two types of high speed solar wind streams emanating from two different solar sources, namely solar coronal holes and flare-associated solar active regions, we wish to point out that the rigidity dependence of the long-term modulation of cosmic rays should vary with the phase of the solar cycle. This is consistent with the recent results (Hatton, 1980; Nagashima and Morishita, 1980a, b). Therefore it would be interesting to look for the approaching declining phase of the sunspot cycle as well as the outcome of the planned solar-polar mission which will provide data for the off-the-ecliptic regions of the heliosphere, where the high speed solar wind streams associated with the solar polar regions are expected to exist throughout the solar cycle.

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